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Optically Powered Speech Communication Over a Fiber Lightguide

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I. INTRODUCTION

The photovoltaic conversion of optical power transmitted over a fiber lightguide can supply electrical power to low-drain semiconductor devices in remote locations. Acoustic powers comparable to those of conventional telephone ringers have been produced[1] in this way by using a fiber-coupled GaAlAs photovoltaic detector[2] to excite an electroacoustic tone generator. It was conjectured[1] that the electrical power for other telephone functions—transmit/receive, dialing, and hook-status recognition—could also be optically supplied, but the signaling techniques appropriate to a dielectric fiber were left unspecified. This note describes the implementation of two-way speech communication between an electrically powered local station and an optically powered station located at the remote end of a 1.1-km-long, single-strand, optical fiber. The remote-station sound alerter has also been operated over this link.

II. SPEECH SIGNALING METHOD

The method used for two-way optically powered speech signaling is illustrated in Figs. 1 and 2. Figure 1 depicts schematically the electronics in an optically powered remote station and the optics in an electrically powered local station. Speech-modulated optical power was launched into the local station end of the fiber from a GaAs injection laser emitting at wavelength λ_1. The remote station contained a fiber-coupled GaAlAs double heterostructure transceiver,[3] denoted PV/LED in Fig. 1, which functioned as a photovoltaic detector when

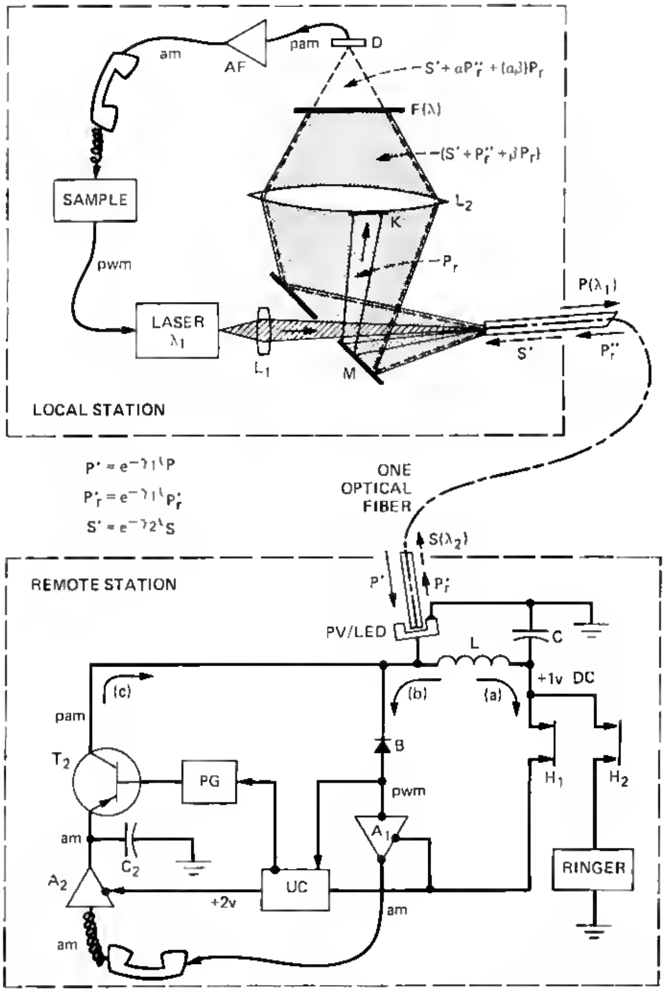

Fig. 1—Schematic of speech signaling method. The fiber length is l. Its transmittance is $\exp(-\gamma_1 l)$ for laser light and $\exp(-\gamma_2 l)$ for electroluminescence, in which γ_1, γ_2 are loss coefficients at the laser and electroluminescence wavelengths. Optical filter $F(\lambda)$ is transparent to electroluminescence but attenuates laser light by factor α. Specular component of reflection P_r is blocked by aperture stop K; diffuse component is attenuated by $F(\lambda)$. Reflection P_r'' is zero during electroluminescence pulse S'. Symbols *am*, *pam*, *pwm* refer, respectively, to amplitude modulated, pulse-amplitude modulated, or pulse-width modulated voltage or current. Switches H_1 and H_2 are shown in OFF-hook state; ON-hook, H_1 is open and H_2 closed. The 1 V and 2 V values indicated for the remote station dc voltages are nominal.

irradiated by light from the fiber and as an electroluminescent emitter when subjected to forward bias. One-volt dc electrical power was generated by photovoltaic conversion of the average power arriving over the fiber and was used to supply the remote station receive/

transmit circuits. The transceiver detected the speech modulation component of optical power, enabling its conversion by these circuits to acoustic power at the earphone, and it emitted electroluminescent pulses, amplitude-modulated by samples of the microphone output voltage. Other authors[4-7] have discussed GaAlAs transceivers in which optical signals are generated and detected on a time-shared basis, with detection typically occurring under zero or reverse bias at very low optical powers. However, we are unaware of previous transceiver applications that combine injection electroluminescence with photovoltaic power conversion, even though these two phenomena have long been known[8-10] as complementary effects in p-n junctions.

A form of pulse-width (or pulse-edge-position) modulation was used to transmit speech information from the local to the remote station. The local station laser was turned off periodically at a rate of $1/T$, equal at least to the Nyquist sampling rate for the speech bandwidth of interest, and was turned back on after a time T_M whose duration was modulated over an interval $\pm \Delta T_M$ in correspondence with samples of the analog output of the microphone. This type of modulation is illustrated in Fig. 2a by the time dependence of the laser power $P_r(\lambda_1)$ reflected from the local station end of the optical fiber. The off-time $(T_M + \Delta T_M)$ was kept small compared to T to maximize the duty factor for transmitted power.

The optical pulses returned from the remote to the local station are illustrated in Figs. 2b and 2c. Laser power, reflected from the remote fiber-air interface and attenuated to level $P_r''(\lambda_1)$ by the fiber losses, arrived back at the local station after pulse round-trip time T_L. Electroluminescence pulse power, spectrally peaked at wavelength λ_2, was generated by discharging capacitor C_2 through transistor switch T_2 with a slight delay T_S from the photovoltaic turn-off instant. A portion of this emission, proportional to the square of the fiber numerical aperture, entered the fiber-guided modes and reached the local station after attenuation to level $S'(\lambda_2)$. Thus, the time-varying optical power incident onto lens L_2 consisted of the laser reflections, $P_r(\lambda_1)$ and $P_r''(\lambda_1)$, and the very much smaller electroluminescence power, $S'(\lambda_2)$, modulated over a range $\Delta S'$ in correlation with the sampled audio-frequency voltage on capacitor C_2. If this flux, depicted schematically in Fig. 2d, is allowed to impinge directly onto detector D, the output becomes noisy and is sensitive to microphonics. This impairment was greatly lessened by the dichroic filter $F(\lambda)$ which attenuated laser light by a large factor α relative to the longer wavelength electroluminescence. The specularly reflected power $P_r(\lambda_1)$ was attenuated an additional large factor β by the aperture stop K. The relative levels of these various powers at detector D, with filter $F(\lambda)$ and aperture stop K in place, are indicated in Fig. 2e.

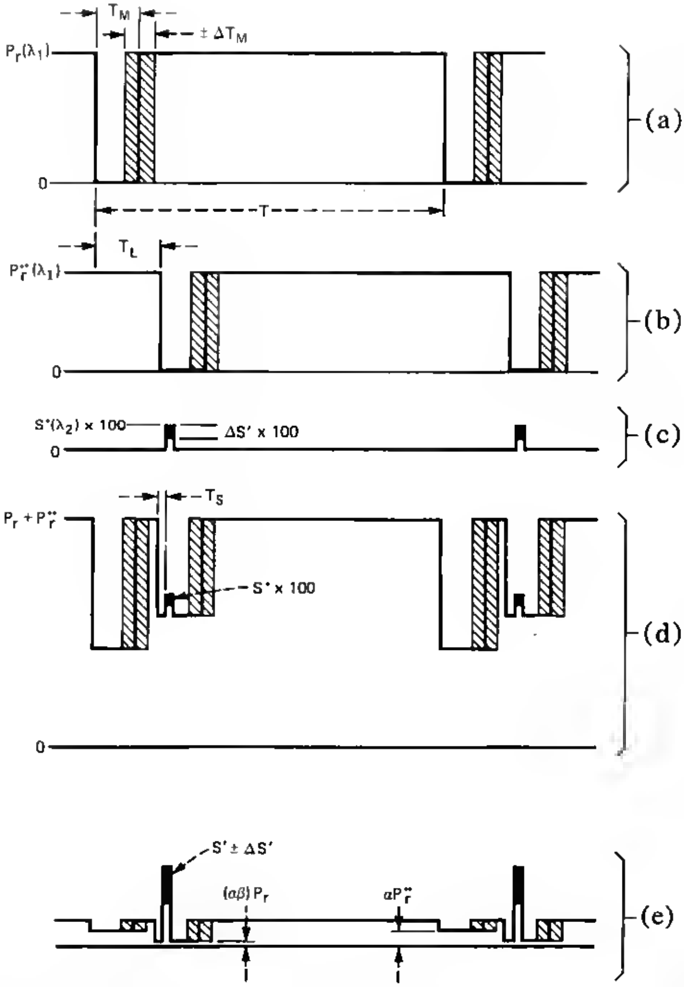

Fig. 2—Optical power levels in the local station. The laser is on most of the time. It is turned off at a rate $1/T$ equaling at least twice the highest speech frequency of interest, and is turned back on after a time T_M. The time T_M is variable over a range $\pm\Delta T_M$ (shaded area) in correspondence with the sampled, amplitude-modulated speech outgoing from the local station. (a) Laser power $P_r(\lambda_1)$ reflected from local station end of fiber. (b) Reflection P_r'' (λ_1) returned from remote end of fiber. The lightguide round-trip delay time is T_L. (c) Transmitted electroluminescence $S'(\lambda_2)$. The electroluminescence pulse is amplitude-modulated over a range $\Delta S'$. Generation of this pulse is slightly delayed (delay-time T_S) with respect to the remote transceiver turn-off time. (d) Superposition of P_r, P_r'', and S' at lens L_2. (e) Optical power incident onto photodetector D. Reflection P_r is reduced by a large factor β at aperture stop K. Filter $F(\lambda)$ reduces remaining light at wavelength λ_1 by a large factor α relative to wavelength λ_2.

III. IMPLEMENTATION

The local and remote stations of Fig. 1 were linked by a 1.1-km-long, fused-silica fiber of 55-μm-diameter core and 0.22 numerical aperture,

whose attenuation was 6.3 dB at the 0.825-μm wavelength of the double-heterostructure GaAlAs laser, and 5.5 dB for the PV/LED electroluminescence spectrum peaked at 0.870-μm wavelength. The round-trip transmission time was $T_L = 11.5$ μs. Lens system L_1 converged the beam through a hole in mirror M to a focus at the fiber, with incidence angle such that specularly reflected light missed the mirror hole and did not refocus into the laser where it could cause cavity destabilization. Filter $F(\lambda)$ utilized the absorption band edge in p-type, $Ga_{0.97}Al_{0.03}As$ to obtain approximately 3-dB attenuation of electroluminescence and more than 20 dB attenuation of laser power.

The circuit branches labeled (a), (b), and (c) in the remote station section of Fig. 1 implement, respectively, the dc-powering, receive, and transmit functions defined earlier. The L-C filter of branch (a) provided ripple-free, 1.0-V power to the bipolar transistors in branches (b) and (c). Figure 3 depicts PV/LED voltage waveforms measured at an optical power sufficient to produce 1.61 mA of short-circuit current; the transceiver zero-volt level is indicated by horizontal arrows. The negative voltage excursion during the optical power OFF-interval is caused by the L-C filter. The clock period T was chosen equal to the 63.5-μs broadcast-television line period in anticipation of future experiments. Amplifier A_1 detected the modulation $T_M \pm \Delta T_M$ corresponding to the optical power OFF → ON transition of Fig. 2a and used constant-current

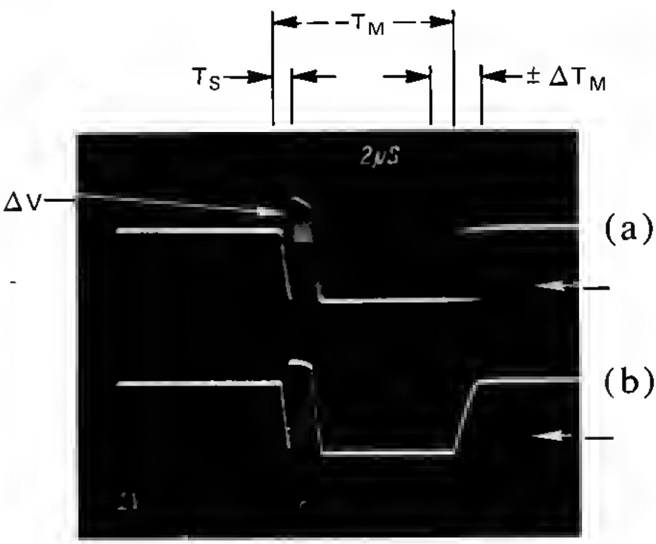

Fig. 3—Voltage waveforms at remote station transceiver. Audio-frequency modulation voltages were present at the local and remote station microphones for trace (a) and were absent for trace (b). Short horizontal arrows indicate the zero-voltage baselines. (Vertical scale 1 V/cm; horizontal scale, 2 μs/cm).

charging of a capacitor to convert the pulse-width variations to an analog audio-frequency voltage at the earphone. The forward voltage needed to produce electroluminescence was obtained by rectifying and filtering the output of a multivibrator-chopper voltage upconverter (UC). The *unrectified* chopper output was shaped by an R-L-C circuit (PG) into a 1.3-μs wide pulse, delayed by $T_S = 0.2\ \mu$s from the optical turn-off instant, which discharged capacitor C_2 through transistor T_2 to produce the electroluminescence pulse. The forward-voltage pulse modulation, labeled ΔV in Fig. 3, corresponds to speech modulation of the C_2 voltage via the crystal microphone and audio amplifier A_2. A compact tone generator (1.8-in. diameter × 0.5-in. thickness) of approximately 35 percent electroacoustic efficiency at 2.0 kHz was incorporated into the remote station telephone base along with the sound-alert circuits.[1] These circuits were activated by depressing the telephone hook switch to close contacts H_2 and open contacts H_1.

IV. RESULTS AND DISCUSSION

Satisfactory two-way speech transmission and vigorous sound alerting at the remote station have been obtained with 14 mW of dc-averaged laser power incident onto the fiber. This power is sufficient to produce short-circuit currents of 1.45 mA in the PV/LED transceiver at the remote end of the 1.1-km fiber. Quantitative studies of audio quality in this link have not been made; however, most observers describe the speech quality (noise, distortion, frequency response) at the remote and local earphones as excellent.

Noise in the remote earphone is inaudible, and excellent speech quality is obtained at the remote station with laser powers smaller than 10 mW incident onto the fiber. Speech volume at this earphone can easily be made uncomfortably loud, but distortion only appears if the local station speech-limiter circuits are maladjusted to permit ΔT_M to approach T_M. A low-level, white-noise-type hiss is present in the local station earphone under most operating conditions. This noise is associated with residual laser radiation present at detector D, and its volume can be varied from barely audible to intolerably loud by adjusting the position of optical filter $F(\lambda)$.

The use of a remote station detector with high photovoltaic efficiency[2] is essential to constructing a remotely located telephone all of whose power can be delivered from a central office. The optical complexity of the remote station is minimized by employing a unitary transceiver which takes advantage of the physical kinship between photovoltaic conversion and injection electroluminescence. Alternative arrangements in which the source and detector functions are performed in separately optimizable devices do, however, possess advantages, including the potential for greatly improving the source bright-

ness and for simplifying the time-sharing schemes. Several such arrangements are currently being investigated and will be reported later.

V. ACKNOWLEDGMENTS

The remote station A_1 amplifier was designed by H. R. Beurrier whose contributions to the later stages of this work have been important. The electroacoustic tone generator was provided by S. Kaufman. Use of GaAlAs "shelf" material for filter $F(\lambda)$ was suggested by R. W. Dixon; our filters were grown and etched by W. R. Wagner. We thank N. E. Schumaker, B. Schwartz, and L. A. Koszi for the PV/LED transceivers, R. L. Hartman for his selection of high performance lasers, and F. V. DiMarcello and J. C. Williams for the fiber.

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